WASTE DISPOSAL IN HORIZONAL SOLUTION MINED CAVERNS CONSIDERATIONS OF SITE LOCATION, CAVERN STABILITY, AND DEVELOPMENT CONSIDERATIONS

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August 4, 1998

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Introduction

Salt caverns created by solution mining have been historically used for brine production, and hydrocarbon storage. Currently, the total number of caverns exceeds 400, the majority occurring in the Gulf Coast in domal salt deposits. Recently, several permits have been issued and waste disposal operations of RCRA exempt oil and gas exploration and production wastes in salt caverns are proceeding. This work is directed at extending the viability of such waste disposal into thinner salt deposits (characteristic of bedded salts) characteristic of many large salt deposits in the Southwest. Specific elements addressed are potential site locations, stability of long horizontal leached caverns, and tradeoff parameter sensitivities in the development of such caverns.

Under companion funding, the Bureau of Economic Geology has been tasked to address the location and characterization of salt deposits, and the Solution Mining Research Institute is investigating the long-term sealing and abandonment of salt caverns.

Provided that sufficient thick and applicable salt deposits can be identified, suitable caverns can be created, and the issues with long term abandonment and sealing can be overcome, the potential for much expanded utilization of salt caverns for waste disposal is high. This research study lays the basis for further economic and site-specific design studies to extend waste disposal in salt caverns into thinner bedded salts.

Solution mining of horizontal salt caverns by controlled leaching via raw or fresh water injection through a long (~2000') horizontal diffuser pipe and removal of the brine downstream has been proposed as a method to controllably develop long horizontal high-aspect ratio (~10:1) caverns in salt (Russo, 1994). The stability of these caverns can be predicted because their geometry can be determined through their development phase and the stress state history can be readily calculated. A computer code HORSMIC (Russo, 1994) was written to predict the growth of these caverns by prescribing dissolution parameters, for example, diffuser pipe hole size and spacing, fresh water injection rate, and insoluble content, etc. The resulting brine density and cavern dimensions are calculated as a function of time by HORSMIC.

Summary

Section 1: Identification of Potential Site Locales

Three potential representative sites for horizontal caverns in bedded salt have been identified and are briefly described below. They are all located in different parts of the Permian Basin of west Texas and are identified here by the geologic core or log assigned to them: DOE 31 Grabbe in the Palo Duro Basin, Jorford English #3 in the Midland Basin, and PDB3 in the Delaware Basin. Minimum depths of study are about 1500'. This depth was chosen so that the sites are then also potentially usable for natural gas storage, and sufficiently deep to preclude local fresh water issues. Thicknesses of salt identified are about 150'. Estimates of volume percent halite/insoluble were made based on lithologic descriptions; insoluble content ranges from 20-30%.

Section 2: Identification of Roof Stability Considerations

Criteria and related design charts were developed to evaluate the stability of insoluble layers formed when leaching caverns in bedded deposits. In some cases, it may be desirous to have a thin, weak bed destabilize and drop during cavern leaching. Under other circumstances, a thick, competent roof bed could be relied upon for cavern integrity.

The solutions presented are applicable to estimate the stability of roof beds in long horizontal caverns. Failure by both shear and tension is considered using the elastic stress solutions for beam and cantilever geometries. The results are presented in the form of design charts which can readily evaluate the stability of a particular interbed thickness given the rock strength, load conditions, and cavern span.

Section 3: Cavern Dissolution Analyses / Parametric Study

A parametric study using HORSMIC was completed to elucidate the effects of freshwater injection rate and insoluble content on the growth of horizontal caverns as a function of time. Leaching time for a specific cavern volume increased with increasing insoluble content at a constant injection rate; leaching time for a specific cavern volume decreased with increasing constant injection rate for a constant insoluble content. Characteristic curves were developed that relate volume and leaching time, brine production rate and leaching time, brine specific

gravity and leaching time and accumulated insoluble volume and leaching time.

Section 1: Identification of Potential Site Locales

Three potential representative sites for horizontal caverns in bedded salt have been identified in west Texas (by Sue Hovorka, BEG). The criteria used to identify sites was simple. Salt formations greater than about 1500' deep and of about 150' in thickness were identified. It was also desirable for additional salt units to overlie the potential cavern site to provide additional vertical permeability barriers.

All potential sites are located in different parts of the Permian Basin of west Texas and are identified by the geologic core or log assigned to them (Figure 1).

The DOE 31 Grabbe well/core (Swisher County) in the Palo Duro Basin was studied in detail (Hovorka, 1986). From that study, halite volume percent was estimated. Lithologic units classified as halite were assumed to be 95% halite; other lithologic units were assumed to have no halite. Using this method two salt sections were identified in this core. One from 1850'-2005' that averaged about 75% halite, and one from 2510'-2690' that averaged about 80% halite. Both sections are halite interbedded with mudstones and siltstones.

For the Jorford English #3 (Crosby County) in the Midland Basin only log data was available, thus no quantitative estimates of halite content could be made. However, two impure salt sections at 1385'-1545' and 2012'-2167' were identified. Both sections interbed salt with mudstone and muddy halite (Hovorka, in prep).

PDB3 well/core (Loving County) in the Delaware Basin was also studied in detail (Hovorka, personal communication). Using the same criteria described above, two salt sections were identified, 1625'-1880' and 1912'-2060' both with about 80-85% halite. This salt is interbedded predominantly with siltstone and mudstone.

All of these sites are considered to be of sufficient lateral extent to site multiple caverns of 1000-2000' in length with a vertical dimension of near 150'.

Section 2: Horizontal Cavern Roof Stability

There is a need to develop preliminary criteria to evaluate the stability of insoluble layers when leaching caverns in bedded deposits. In some cases, it may be desirous to have a thin, weak bed that may leach or become unstable and drop during cavern leaching. In other cases, it may be desirous to have a thick, competent roof bed that can be relied upon for cavern integrity. In either case, the stability of inter-beds needs to be examined, and criteria developed for evaluating various conditions that may be encountered during site selection and characterization.

In the absence of site specific strength data, some guidance can be given based on published rock strengths and simple beam analyses. The salt basins of West Texas have interbeds of anhydrite, mudstone, and sandstone of various thicknesses. The published[1] laboratory tensile strengths of these types of rock seldom exceed 2200 psi, but in the field insitu fractures can reduce the strength to zero. Site specific core examination would enable characterization of any jointing and empirical methods could be used to estimate insitu strength. Laboratory tests of flexural strengths can be used to obtain flexure data. For now, the flexural strength of the rock will be assumed equal to the tensile strength. The shear strength of the rock may be approximated as 60 percent greater than the tensile strength. Both failure by shear and tension will be examined in the following analyses.

The elastic stresses for a fixed end beam are well known and can be used to estimate the stability of roof beds in long horizontal caverns. Fixed end conditions (as opposed to other end boundary conditions) best represent interbeds at depth[2]. The interbed is assumed to be an independent structure, loaded on top by lithostatic pressure and on the bottom by cavern fluids. The degree that an interbed can be assumed as an independent structure (i.e. a beam) depends upon the cohesion between the layers. If the two layers have an interface between them that is cemented, then they may act as one structure. Again core examination would help determine the degree of cementing (if any) between layers.

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[1] Touloukian, Y.S. and C.Y. Ho. Physical Properties of Rocks and Minerals. McGraw Hill, 1981.

[2] Adler, L. and M. Sun. Ground Control in Bedded Formations. Virginia Polytechnic Institute, Blacksbursg, Va, 1968.

The top loading may be assumed as lithostatic especially if the overlying layer is salt and hence subject to creep. The bottom loading on the roof bed will be the cavern gas or fluid and its pressure may vary. While leaching, the cavern fluid pressure will be equal to approximately one-half of lithostatic pressure. Lithostatic pressure is often assumed to be 1 psi per ft of depth. If gas storage is ever contemplated in the cavern, then the worst case loading may be assumed during a blowout of the wellhead where the gas is completely lost and the roof pressure goes to atmospheric. Under these conditions the loading of the roof bed may be assumed to be equal to its depth, that is one psi per foot of depth. For liquid caverns, the minimum cavern pressure would be a function of the density of the fluid being stored. In the case of crude oil, it may be determined by multiplying the cavern depths times a typical oil pressure gradient of 0.37 psi per ft of depth. Any pressure exerted by the cavern fluid against the roof would improve stability by reducing the effective load on the roof span.

No end loads were applied to the beam. End loading may occur due to creep, however the solution for end loading conditions is indeterminate. Empirical data[3] shows that if an end load equivalent to the vertical load is applied the solutions are not significantly different (remains below 5 %) until the span length to thickness ratio exceeds 25 for the conditions evaluated in this memo. Since these are well above the typical ratio required for failure, end loading need not be considered in these preliminary analyses.

Figures 2 and 3 show the required strength of the roof rock as a function of the roof span to bed thickness ratio for various pressures. If the shear and tensile strengths of the roof bed are known along with the effective vertical stress acting on the bed, then the acceptable bed thickness may be calculated for a given cavern roof width. Different bed thicknesses will be estimated from Figures 2 and 3. For stability, the thicker of the two should be used. An appropriate safety factor should be applied to the result. This results in even a thicker bed than indicated in the charts if stability is desired. In some cases, it may be desirable to have the roof beds fail during leaching to create taller caverns. The same procedure could be used to determine bed thicknesses that are likely to fail during leaching. In this case, the safety factor would be applied so

[3] Hsu, T.H. Stress and Strain Data Handbook. Gulf Publishing Co., Houston, 1987.

that the bed thickness is thinner than indicated by the charts. The various cavern operating pressures must be examined because a bed may be stable during leaching, but it may fail during dewatering of the cavern (for gas storage).

The failure mode in Figure 2 is shear failure at an end of the roof span. The failure mode in Figure 3 is tensile failure in the center of the roof span. For typical rock strengths where the shear stress is 60 percent greater than the tensile strength, shear failure will dominate below roof width to bed thickness ratios of less than 0.9. This is important for the next step in the procedure which is to examine the stability of the initially fractured roof bed. It is possible that a single fracture will not cause the roof bed to detach and fall to the cavern floor. The initial fracture may occur, separating the roof bed from its overlying bed to form a cantilever. The roof bed would be detached at one end and loaded by its own weight. Its span could be equal to either the cavern width if it was a shear failure, or one-half the cavern width if a tensile failure caused it to crack. In either case, Figure 4 can be used to determine whether the detached roof cantilever is likely to fall or just hang. Cavern operating pressure is not important is this analysis since it will be applied to both the top and bottom of the cantilever, thus canceling and not adding any effective force on the structure. If the bed does not fall, the maximum deflections may be estimated from Figure 4 assuming a typical elastic modulus of 2.9×10^6 psi. Since deflection is inversely proportion to the modulus, more accurate estimates of deflection can be derived from Figure 4 once the specific properties of a rock become known. These obviously occur at the free end of the bed.

As an example, consider a gas storage cavern is planned at 2000 ft below the surface. The tensile strength of the inter-beds was measured at 1000 psi. At the cavern depth, the lithostatic pressure loading the top of the roof bed is assumed to be 2000 psi. During leaching, the brine head in the cavern will provide a pressure along the bottom of the bed approximately equal to 1000 psi. This effectively loads the roof bed at 1000 psi. During cavern operation, the gas pressure may drop to a low value and in the case of an accidental blowout at the wellhead, the cavern pressure could fall to near atmospheric. Therefore the limits on loading the roof bed range from 1000 to 2000 psi. The estimated shear strength is assumed to be 60 percent greater than the tensile strength or 1600 psi. This strength is far above the 1000 to 2000 psi load curves in Figure 2, therefore stability will be controlled by tensile failure, rather than shear failure. As shown in Figure 3, a 1000 psi tensile strength results in roof width to bed thickness ratios of 1 to 1.4 for 2000 and 1000 psi loads, respectively. Therefore, the bed thickness should be greater than the roof span to be stable during the operational phase of the cavern. During leaching, bed thicknesses less than 70 percent of the length of the roof span are predicted to fracture near the middle. According to Figure 4, when the roof bed fractures and starts to sag from the cavern roof, it will fail in tension if its thickness is less than 30 percent of its length or 15 percent of the cavern roof span. Given this information, the roof of a cavern can be sized for a particular site or the appropriate site selected for a given cavern size. In practice, some compromise and judgment will be needed.

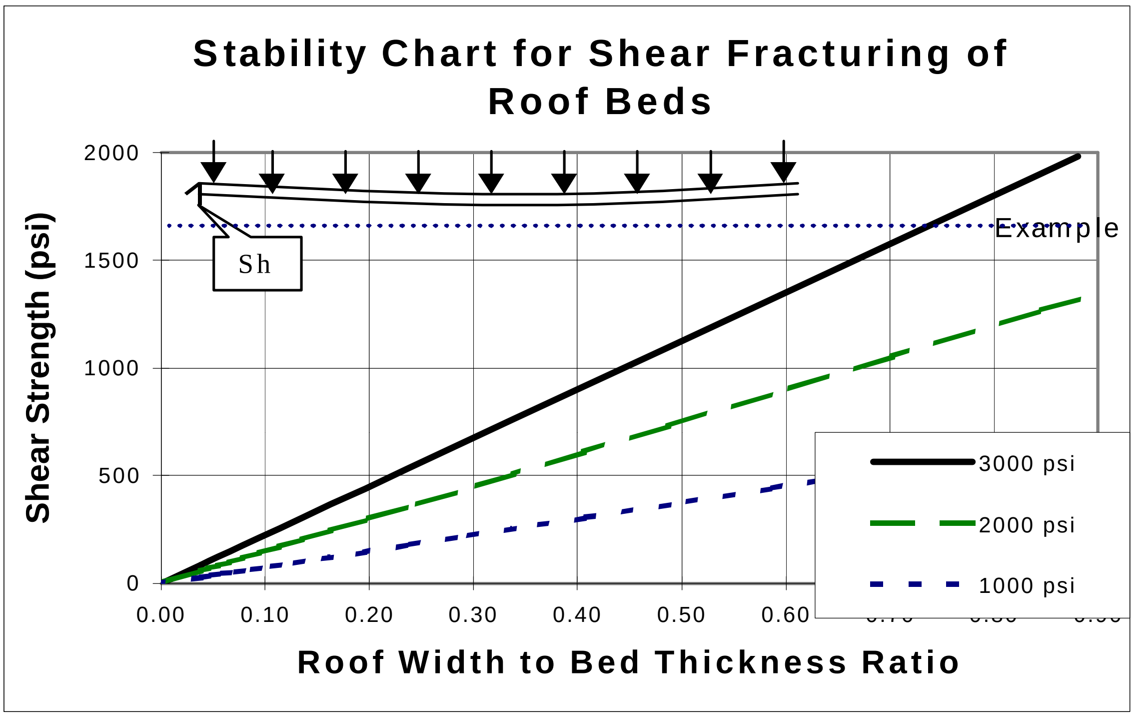

Figure 2. Stability Chart for Shear Fracturing Beds

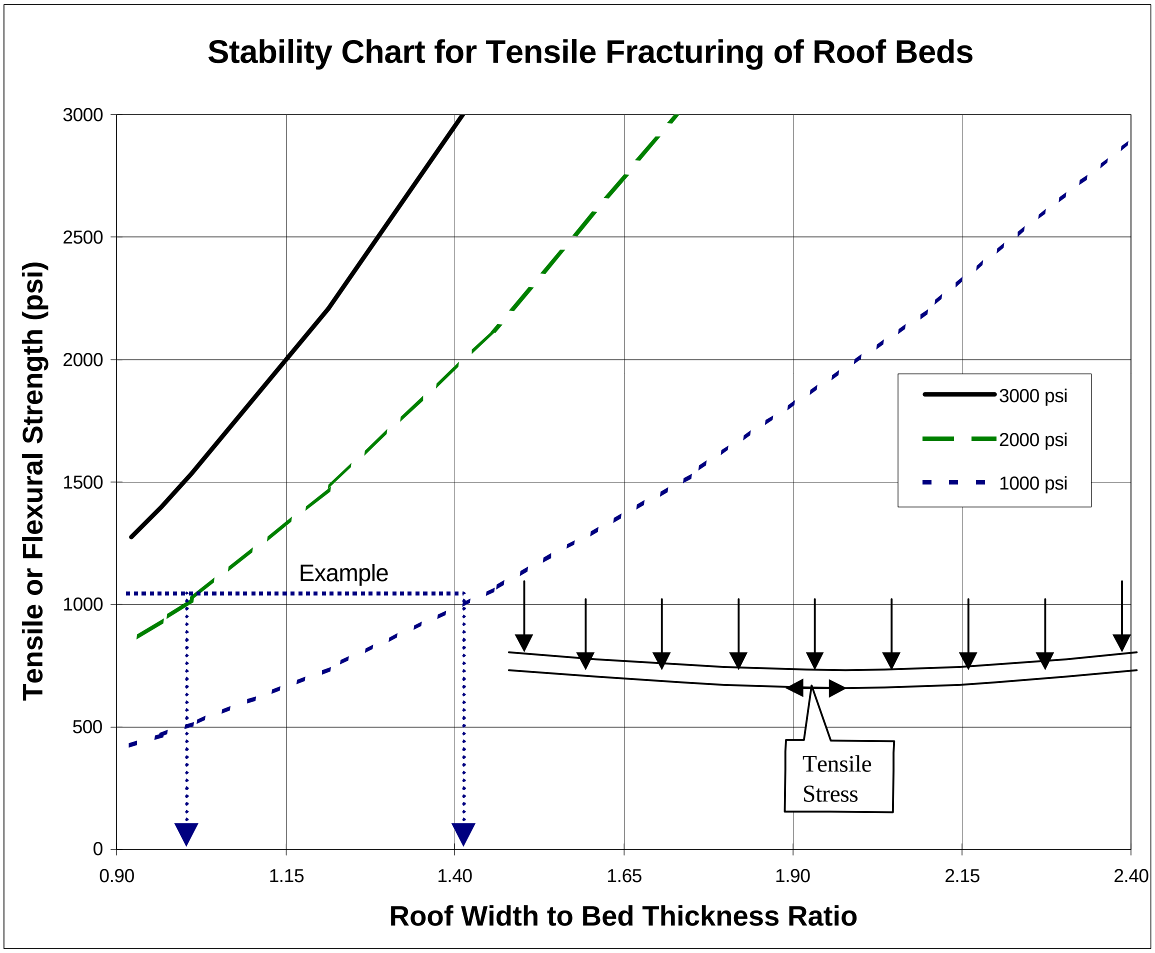

Figure 3. Stability Chart for Tensile Fracturing of Roof Beds

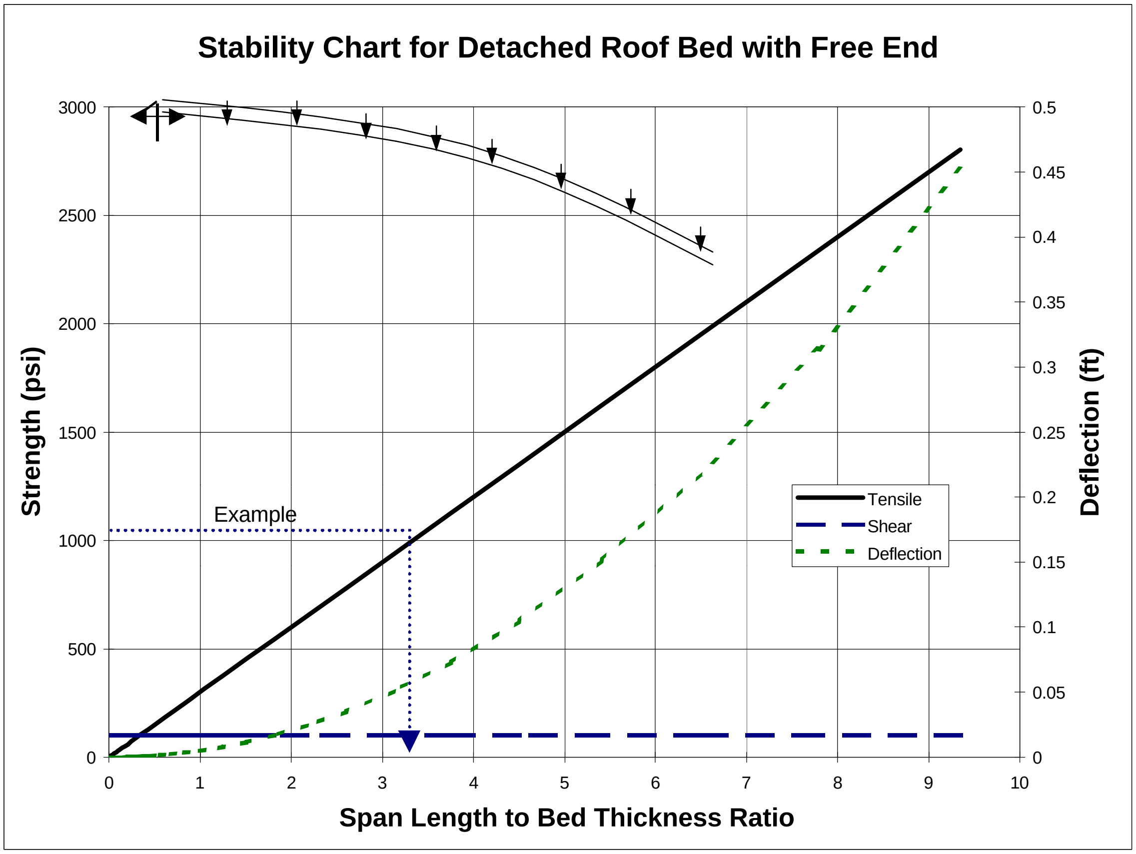

Figure 4. Stability Chart for Detached Roof Bed with Free End

Section 3: Parametric Study for Horizontal Cavern Dissolution

A parametric study was completed to provide a tool to help predict how long horizontal caverns can be developed in bedded salt. Given prior knowledge of insoluble content, this information can be used with the parametric curves generated in this study to determine cavern cross-sectional aspect ratio, volume and respective cavern width, brine production rate and specific gravity, insoluble volume and level, and ceiling level at a predetermined fresh water injection flow for various stages or time in the leaching process.

In the process of generating the families of parametric design curves, several assumptions were made relative to the physics involved[4] and the code input parameters. Input parameters that were kept constant were the number of holes and uniform spacing and uniform size of the holes in the freshwater injection tube, the pipe dip angle from horizontal (kept at 5 degrees), the injection pipe inside and outside radii, initial cavern hole diameter, and initial injection depth (centerline of the injection pipe). The specific gravity of the injected water was assumed to be 1.002 at a temperature of 75°F and the initial specific gravity of the cavern fluid was assumed to be 1.2. Computer outputs were generated for insoluble fractions from 0.0 up to 0.4 for various incremental fresh water injection flow rates for a 2000 ft long design cavern.

In developing a cavern a gas or oil blanket can be used above the injected water to prevent or minimize the leaching of the ceiling. The effect of this would result in a wider cross-sectional cavern. The generated curves rely solely on the fraction of insolubles in the bedded salt without the use of a blanket to control cross-sectional aspect ratio. A gas or oil blanket can be injected at any time in the development of a cavern to maintain the ceiling level at a given depth and enhance cavern width.

The output information for all the computer runs were reduced and tabulated for all the variable design parameters at the different water injection flow rates. The parametric design curves were generated from these tables. Design parametric charts for the 150 MB/day fresh water injection rate series are shown in Figures 5 through 10. Three dimensional plots that show the cavern shape for different insoluble fractions were also generated

[4] Russo, A.J., 1994, “A User’s Manual for the Computer Code HORSMIC”, SAND93-3841

and used to generate a graph used to predict horizontal cavern cross-sectional aspect ratio as a function of insolubles in the bedded salt (Figure 11). Figure 12 shows the cross-sectional cavern width for a 2000 ft long cavern of different leached out volumes for different insoluble fractions. It is useful to know the cavern width in order to determine the horizontal roof stability of an insoluble layer as described in Section 2 of this report.

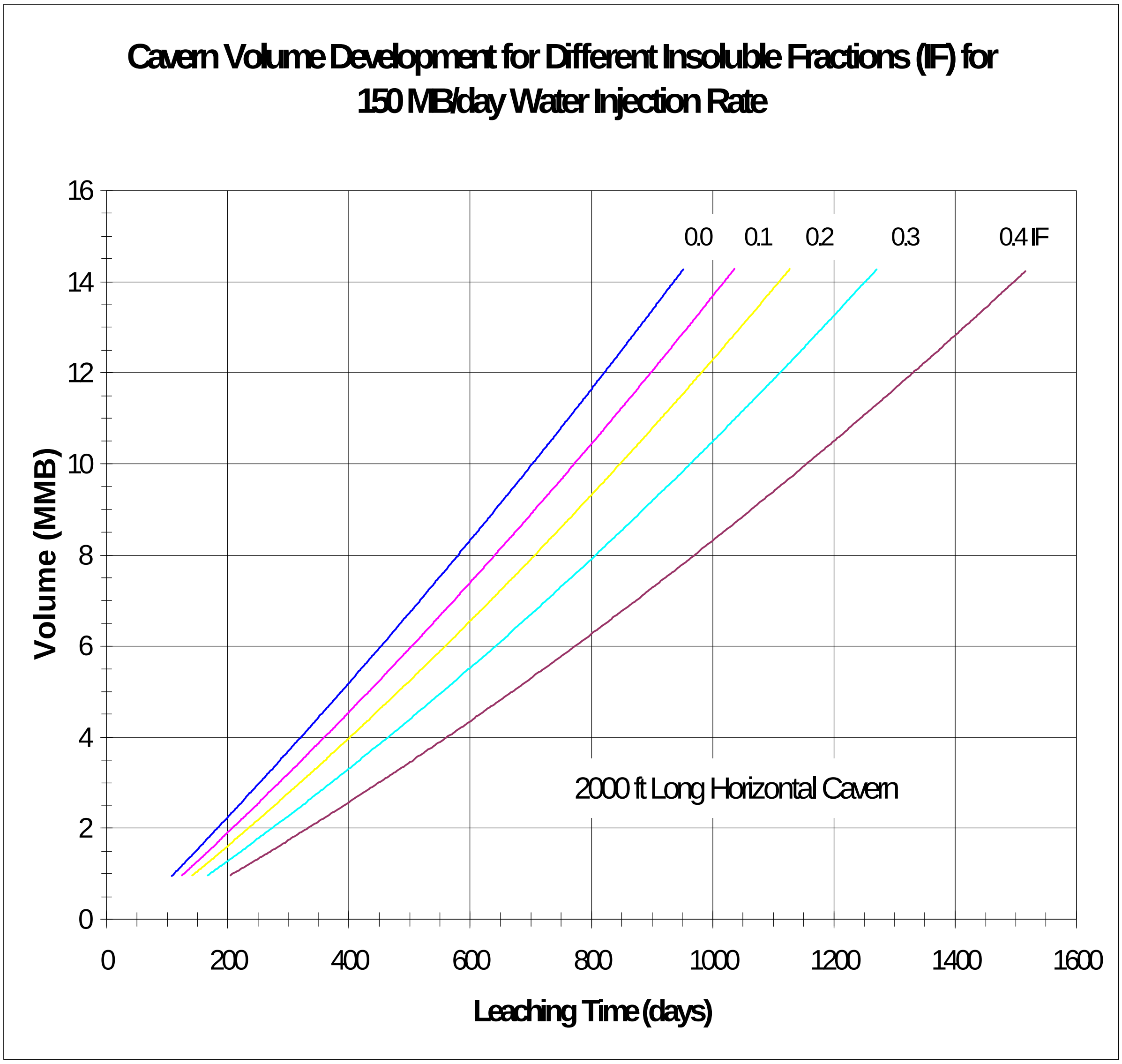

Figure 5. Cavern Volume for Given Leaching Time for Various Insoluble Fractions

Additional analysis was performed to determine the effects on cavern length. A 1000 ft length cavern was evaluated and compared to the original

2000 ft long cavern. Since the length was reduced by a factor of two, the evaluated fresh water injection flow rates and volumes were also reduced to half the original values in order to determine the effects of the design parameters. The compared results showed that leaching time, brine outlet specific gravity, insoluble level, and ceiling level ratios were very close to one. The brine output production rate and volume of insoluble ratios were very close to 0.5 (the same as the ratio of the two different lengths). The cross-sectional aspect ratio (width/height) of the caverns remained the same for both caverns since this dimensional feature is a function of insoluble fraction and is independent of length and water injection flow rate.

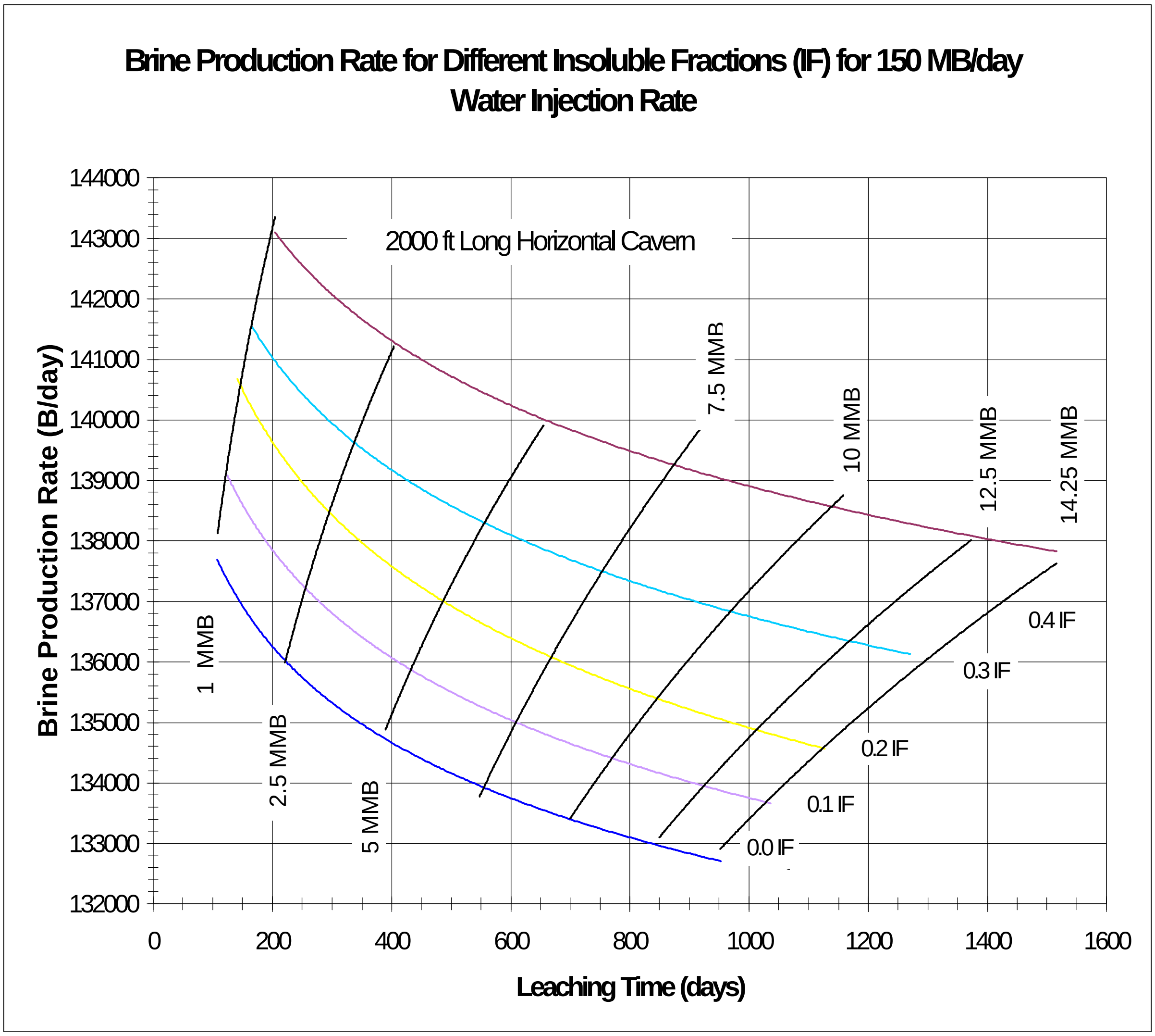

Figure 6. Brine Production Rate for given Leaching Time for various Insoluble Fractions

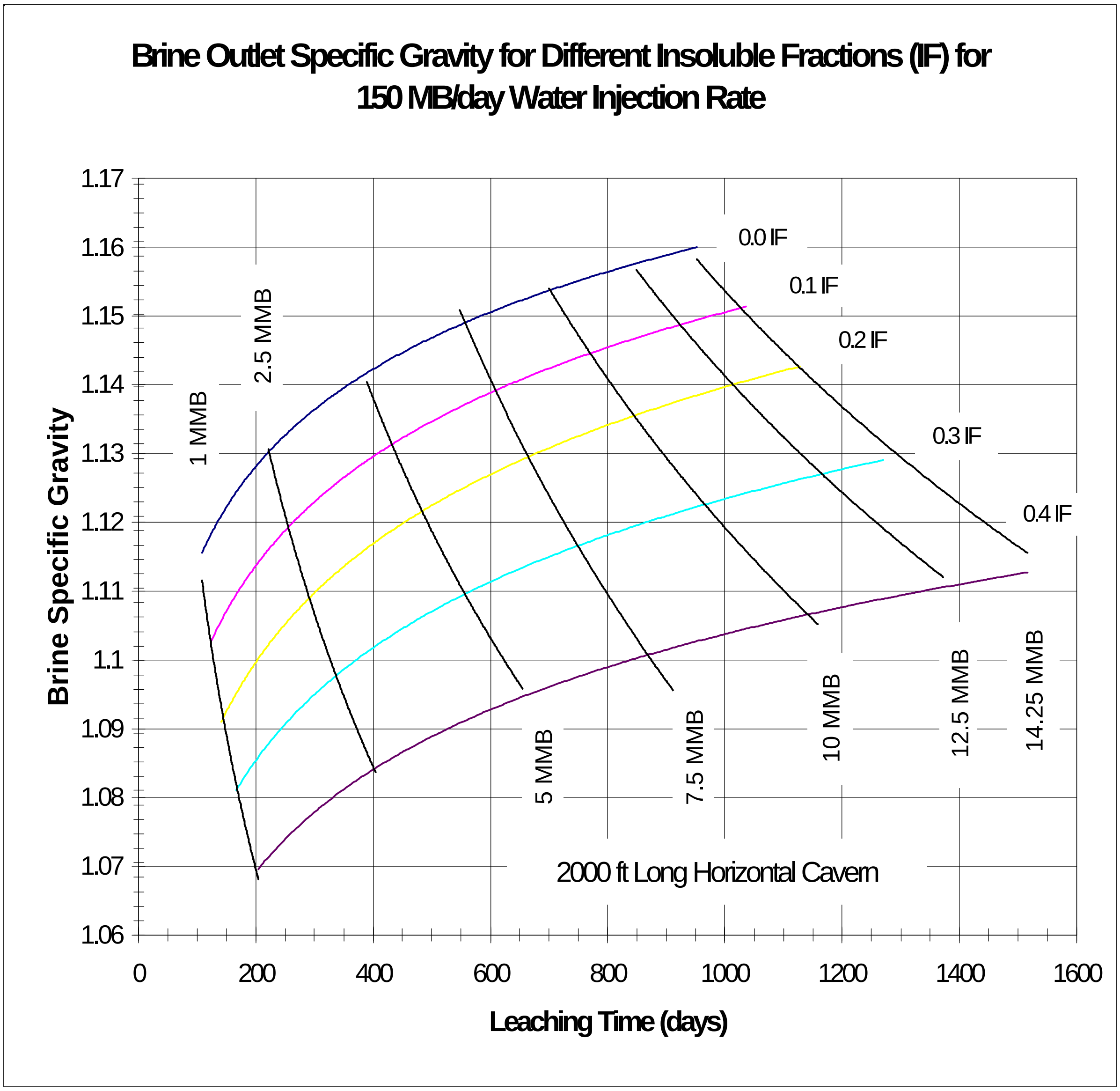

Figure 7. Brine Specific Gravity for Given Leaching Time for Various Insoluble Fractions

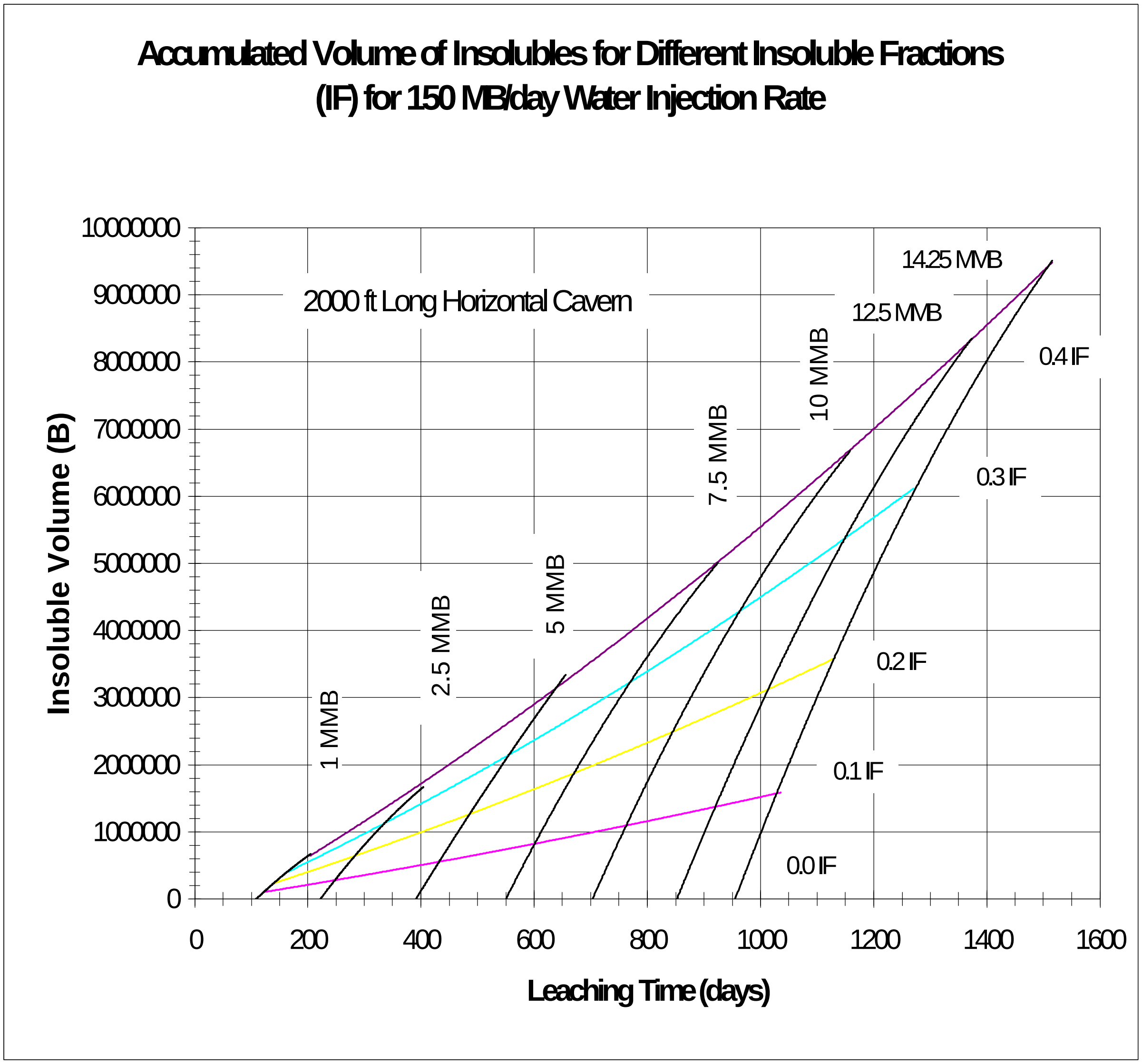

Figure 8. Insoluble Volume for Given Leaching Time for Various Insoluble Fractions

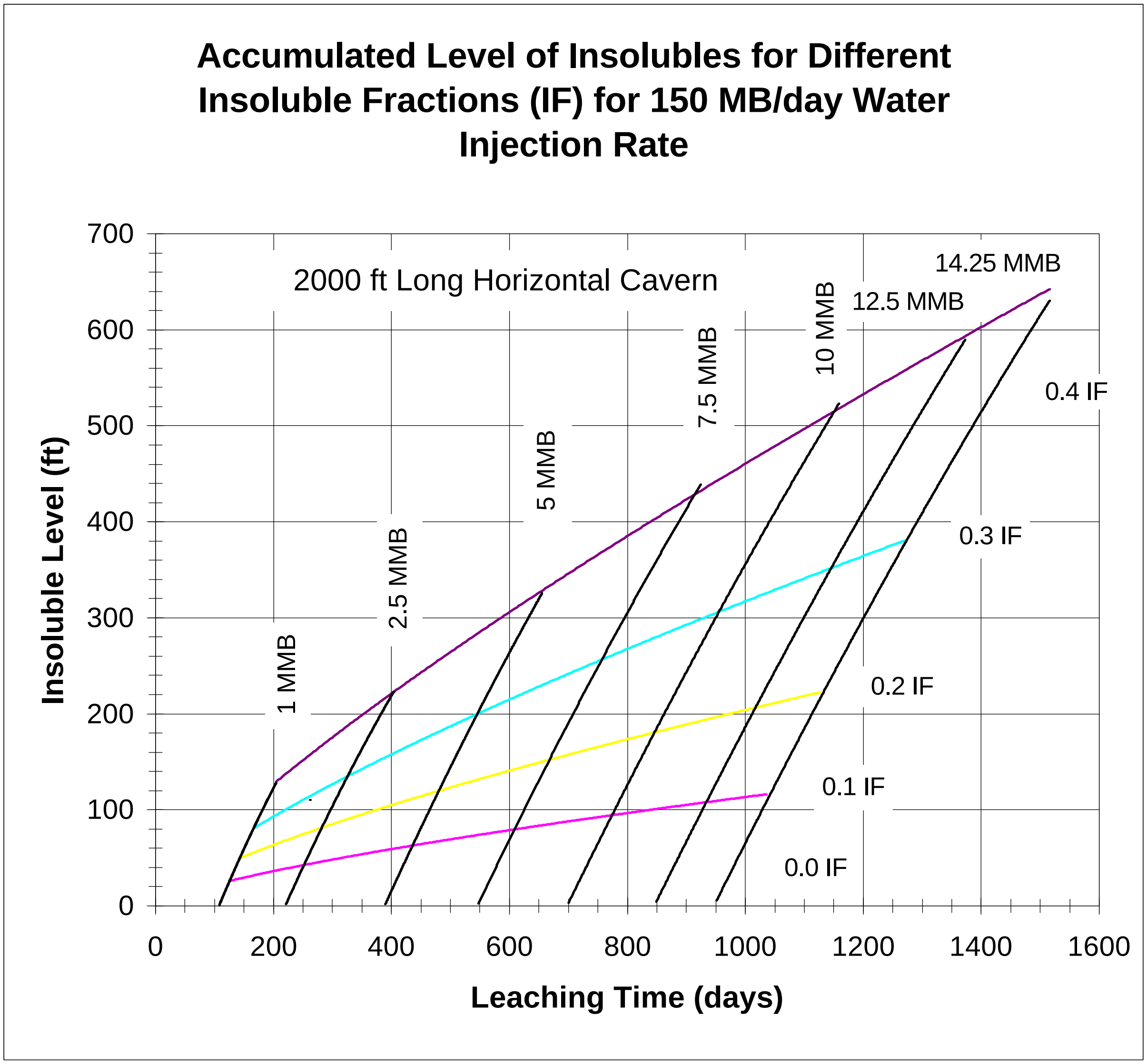

Figure 9. Accumulated Insoluble Level for Given Leaching Time for Various Insoluble Fractions

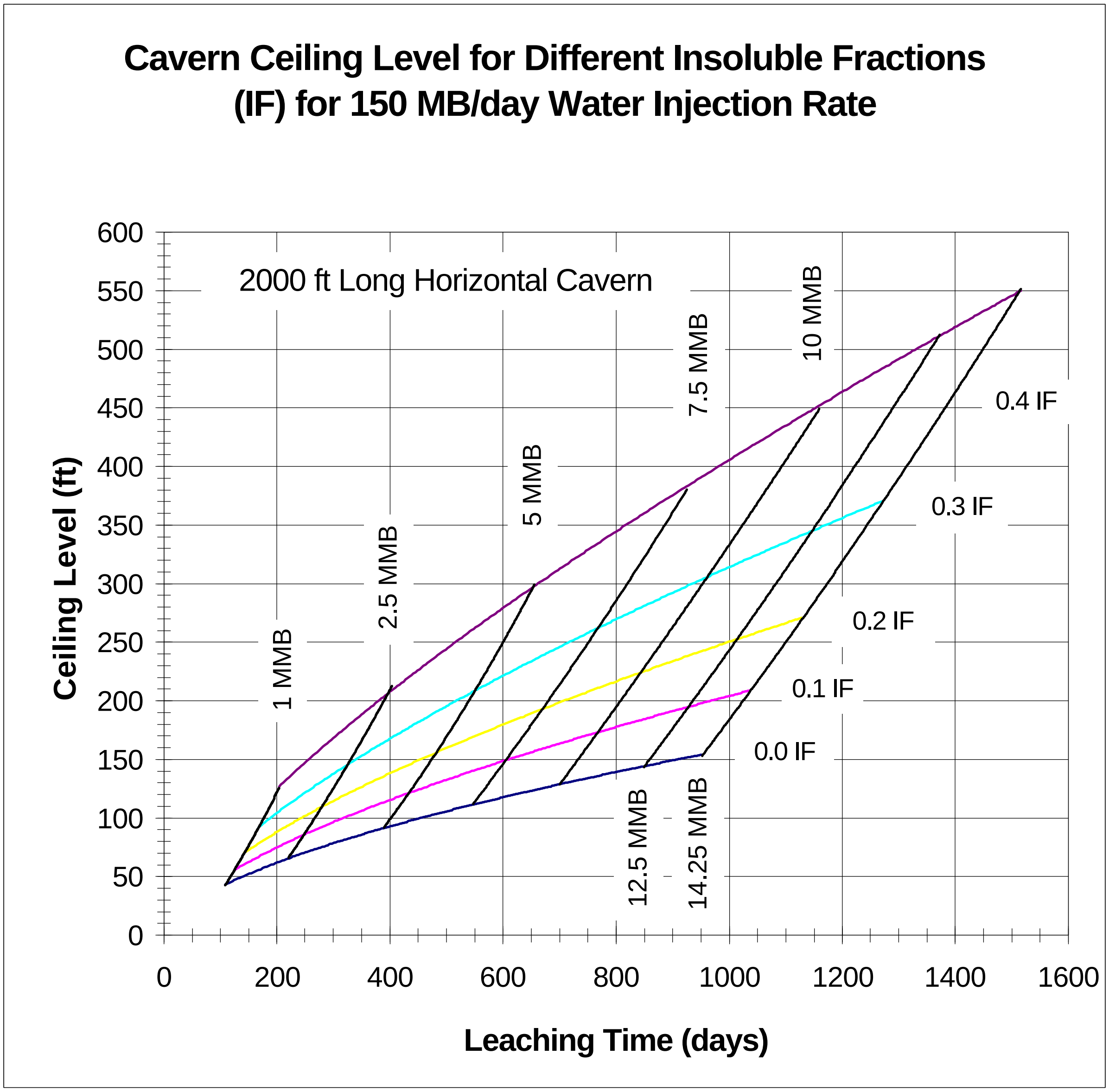

Figure 10. Cavern Ceiling Level for Given Leaching Time for Various Insoluble Fractions

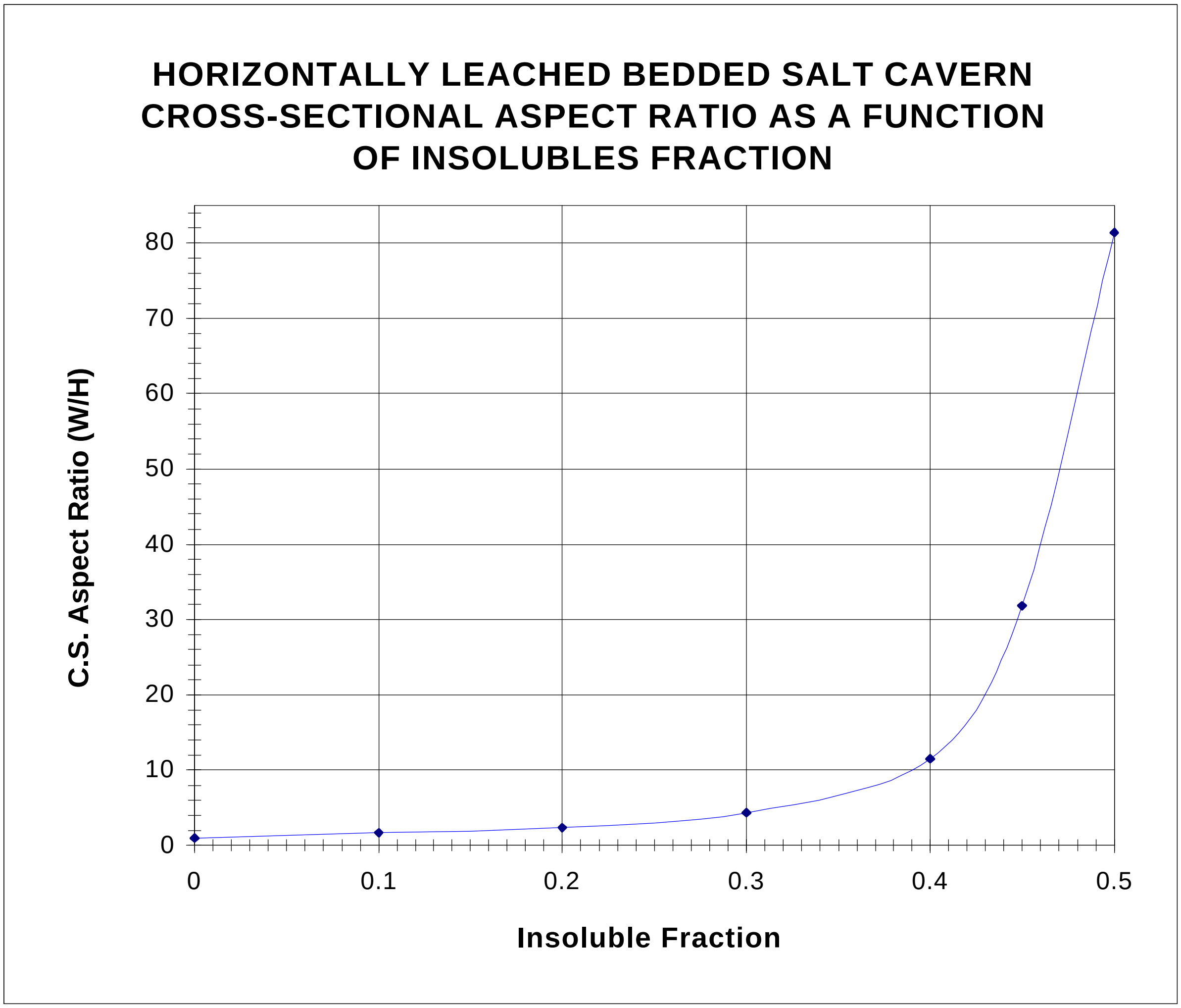

Figure 11. Cavern Cross-Sectional Aspect Ratio as a Function of Insoluble Fraction

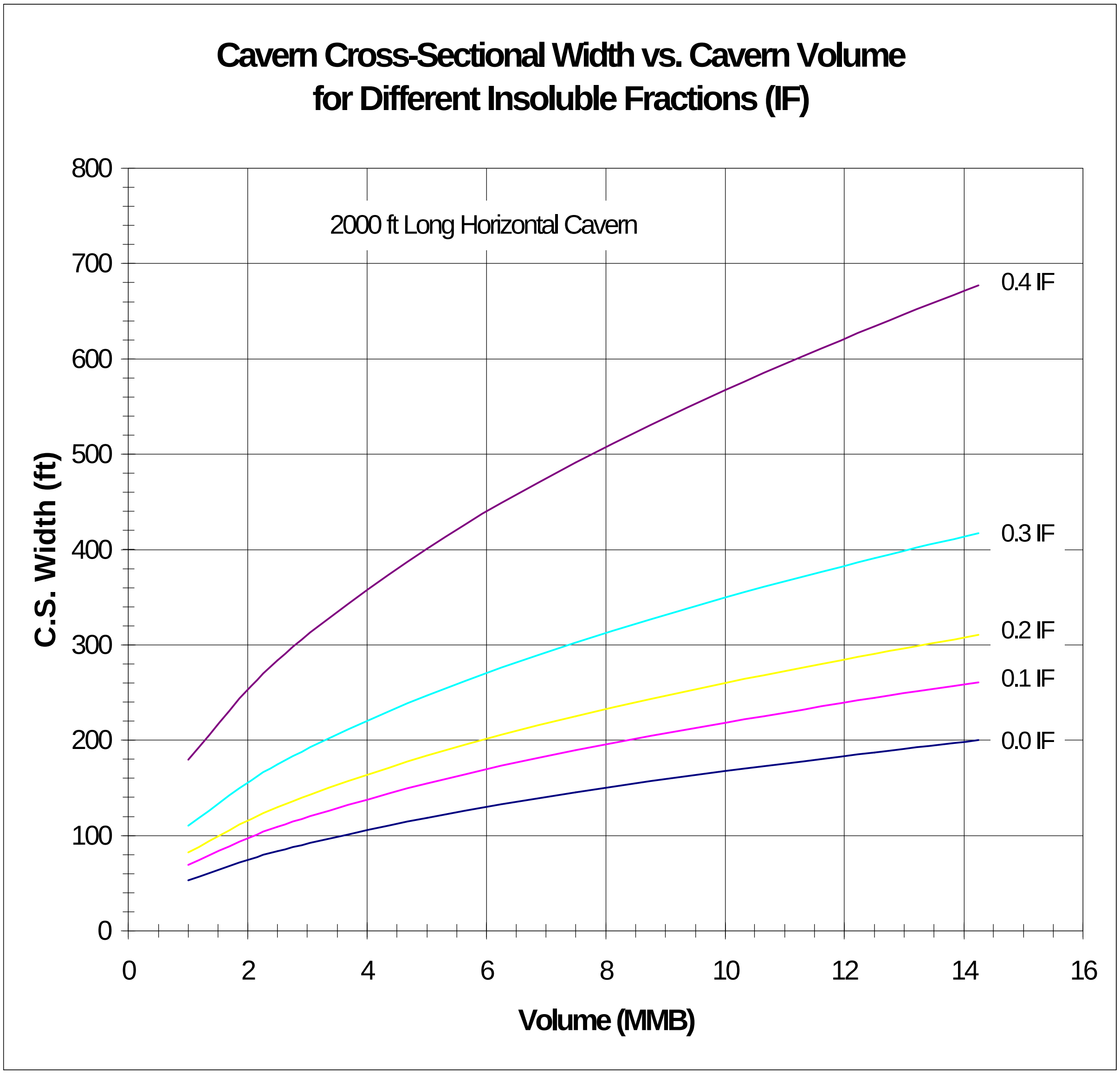

Figure 12. Cavern Cross-Sectional Width for Given Leached Volumes for Various Insoluble Fractions

In summary, the generated parametric curves are a useful design tool in estimating the time it takes to develop a horizontally leached cavern of a desired volume. The curves are also useful in helping predict cross-sectional shape, instantaneous brine production rate and specific gravity, volume and level of insolubles, and cavern ceiling level and width. Cavern width is of particular interest in helping determine insoluble ceiling layer stability.

Conclusions

This work has identified and brought together aspects important to development of long horizontal caverns in bedded salt suitable for waste disposal (or hydrocarbon storage).

Representative potential sites have been identified in west Texas. These sites have sufficient salt thicknesses and areal extent to accommodate arrays of long horizontal caverns. Many other bedded salt sites exist in the southwestern, midwestern and northeastern U.S. These sites will require more specific characterization to be considered for development.

For both waste disposal and product storage, is most likely best economically feasible if cavern siting is near the waste or product production site. This will minimize transportation costs.

Preliminary cavern stability considerations have been addressed wherein criteria and related design charts were developed. This preliminary work can be used for guidance in conceptualization, however assumptions relative to rock mass material behavior and strength were made. To make this preliminary work more meaningful, when a site is to be developed these properties should be experimentally determined. The strength of salt bearing and leached salt bearing rocks is to a large extent unknown in the rock mechanics community, because the need for such knowledge has thus far not existed. This study also assumed These aspects include potential sites for cavern development, important considerations for roof stability of caverns, and the effect of variations of parameters that are likely important in cavern development in bedded salt, injection rate and insoluble content.

Finally a solution mining code (HORSMIC) was exercised to provide a preliminary understanding of how cavern geometry will evolve during the course of dissolution. Utilization of the code was portrayed in terms of a study to evaluate basic parameters (for example, fresh water injection rate and insoluble content) that are likely important in cavern development in bedded salt.

In summary, this report provides a means to make positive preliminary judgements towards the siting, development and stability of long horizontal caverns in bedded salt.